SPEECH RECOGNITION IN BACKGROUND NOISE: AN EVIDENCE-BASED REVIEW

Capstone Project

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By

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ABSTRACT

Audiologists who work with the older adult population frequently hear, “I can understand you fine in your office, but when I am in the ‘real world’ I really struggle.” Audiologists are well aware that communication does not always occur in quiet settings such as an office or sound booth, but instead often occurs in the presence of background noise. As people age, pathological changes along the entire auditory pathway contribute to sensorineural hearing loss and make speech understanding in background noise increasingly difficult. Within the profession of audiology, tradition has dictated that: a) speech testing is performed in quiet, and b) hearing aids are utilized as the main, if not sole, rehabilitative strategy for sensorineural hearing loss. However, what is tradition is not always what is best practice. This paper serves to review the evidence which emphasizes the need for speech testing in the presence of background noise, as well as the need for a rehabilitation plan beyond the hearing aid fitting. A review of the senescent changes to the auditory system will also be discussed.

Dedication

This Capstone project is dedicated to my family and friends, who have patiently supported and encouraged me through the rigors of graduate school. I would also like to dedicate this project to my fiancé Alex. Without his insistence that I spend Saturday afternoons researching and writing instead of relaxing, I would still be working on this project today.

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Chapter 1

Introduction

The complicated link between hearing loss, communication, and background noise has been well-researched by hearing professionals. Background noise is a constant challenge for hearing-impaired patients, magnifying the communication difficulties this population already faces. It is therefore also a challenge for audiologists, who struggle to meet their patients' communication needs. Even as the effects of background noise complicate the lives of patients and audiologists alike, the assessment and management of communication difficulties in background noise are still lacking in most audiology practices (Wilson, 2004). As the field of audiology has begun to shift from a diagnostic, product-centered field toward a more rehabilitative, patient-centered profession, more emphasis needs to be placed on addressing communication difficulties in background noise.

Chapter 2

The aging auditory system: Anatomical and physiological changes

It has been well-established that speech understanding ability decreases with age, particularly in challenging or noisy environments (Gordon-Salant & Fitzgibbons, 1995b; Helfer & Wilber, 1990; Wiley et. al, 1998; Committee on Hearing and Bioacoustics and Biomechanics [CHABA], 1988). This decline arises from the anatomical and physiological changes that occur to the auditory system with age. Pathological changes to the peripheral and central auditory system, as well as to general cognitive processing result in speech understanding difficulties that cannot always be explained by elevated auditory thresholds alone (Chisolm, Williot & Lister, 2003; Humes, 1996, CHABA, 1988).

Though sensorineural hearing loss arises from many causes, it is most often associated with damage to the outer hair cells (OHC) of the cochlea (Shuknecht & Gacek, 1993). While OHC damage does not contribute to significant speech recognition difficulties in quiet, it often results in considerable difficulty in background noise, as several psychoacoustic processes that help separate speech from background noise become impaired (Chisolm et al., 2003). In particular, it is believed to be the loss of the compressive function of the OHCs that causes speech-in-noise difficulties (Oxenham & Bacon, 2003). While the OHCs normally compress mid-intensity inputs, damage to the OHCs results in a more linear system.

One consequence of this loss of non-linearity is the phenomenon of recruitment, commonly defined as “abnormal growth of loudness.” For many people with sensorineural hearing loss, sounds change rapidly from inaudible to uncomfortably loud, as normal perception of soft, mid and loud sounds are lost (Oxenham & Bacon, 2003). Persons experiencing recruitment may find it intolerable to listen to speech in background noise.

Another consequence of OHC damage is the reduced frequency selectivity of the cochlea. In a healthy cochlea, the compressive function of the OHCs results in a sharply-tuned response at low-input levels and a much more broadly-tuned response at higher input levels (Oxenham & Bacon, 2003). When the OHCs are damaged and this compressive function is lost, the cochlea’s response “resembles the broad tuning found at the highest sound levels in the normal cochlea” (Oxenham & Bacon, 2003, p. 355). Loss of frequency selectivity in hearing-impaired adults is evidenced by measures of critical bandwidth; the range of frequencies to which each point along the basilar membrane responds. Masking experiments reveal the bandwidth of noise needed to mask a tone, so that further increases in noise bandwidth do not result in additional masking, is wider for hearing-impaired subjects than normal-hearing subjects, implying a loss of frequency selectivity (Florentine, Buus, Sharf & Zwicker, 1980; Healy & Bacon, 2006). This loss of frequency selectivity is detrimental to speech understanding in noise, because more noise is likely to fall in the critical bands of the speech signal, thus masking it (Healy & Bacon, 2006).

OHC damage also results in temporal processing deficits, which are strongly linked to the loss of compression as well. Oxenham and Bacon (2003) describe two examples of impaired temporal resolution due to loss of compression. First, individuals who are hearing-impaired have higher-than-normal thresholds for detection of temporal gaps in narrowband noise. Peaks in the noise are thought to be exaggerated by the effects of recruitment and mistaken as temporal gaps. Second, hearing-impaired individuals show a slower recovery from forward masking than normally-hearing individuals. The effects of the masker decrease faster when the signal is compressed; a phenomenon that is lost in individuals with OHC damage. The clinical implications of these two phenomena are that listeners with hearing impairment have a more difficult time separating the speech signal from the inherent fluctuations in many background noise stimuli (Oxenham & Bacon, 2003).

In addition, OHC damage may also result in reduced temporal integration, meaning that increases in signal duration result in smaller changes of threshold (Moore, 1996). Clinically, Moore (1996) explained that reduced temporal integration could mean that “the loss of audibility for brief speech sounds (such as plosives), relative to normal, would be less than the loss for longer duration sounds (such as vowels)” (p. 143). However, it should be noted that theoretically, temporal processing may be better in hearing-impaired versus normal-hearing individuals. This is due to the reciprocal relationship between frequency resolution and temporal resolution; as frequency resolution is worse individuals with hearing impairment, it stands that temporal resolution may therefore be better (Moore, 1996).

While not as vulnerable to damage as the outer hair cells, inner hair cell damage also leads to significant speech recognition difficulties. Inner hair cell loss, which is almost always associated with loss of spiral ganglion cells, results in a specific type of sensorineural hearing loss that Schucknecht and Gacek (1993) define as “neural sensorineural hearing loss”. With neural sensorineural hearing loss, speech recognition scores, even in quiet, are poorer than expected given pure tone thresholds. This is evidenced by research on the topic of cochlear dead regions, where clusters of IHCs and/or neurons don’t function or function poorly, and a pure tone producing peak vibration in that area is only heard by spread of excitation to surrounding neurons (Moore, 2004; Preminger, Carpenter & Ziegler, 2005). Preminger et al. (2005) measured speech recognition in noise by administering the Quick Speech-In-Noise (QuickSIN) test (Killion, Niquette, Gudmundsen, Revit & Banerjee, 2004) to 49 subjects. The authors confirmed that 29% of subjects had cochlear dead regions using the Threshold Equalizing Noise Test (TEN) (Moore, Huss, Vickers, Glasberg & Alcantara, 2000). With the TEN, listeners detect sinusoids in the presence of a broadband noise stimulus. Listeners with dead regions show greater-than-expected masking in the frequencies where dead regions are located. After accounting for hearing loss configuration and presentation level, the researchers found that subjects with cochlear dead regions performed significantly worse on the QuickSIN than subjects with no dead regions, suggesting greater difficulty understanding speech in background noise. Subjects with cochlear dead regions also perceived poorer subjective hearing aid benefit, as measured on the Abbreviated Profile of Hearing Aid Benefit (APHAB) (Cox & Alexander, 1995), than listeners without dead regions. Listeners with dead regions reported significantly less hearing aid benefit in noisy or reverberant listening conditions, suggesting cochlear dead regions limit the effectiveness of hearing aids.

In addition to peripheral changes, pathological changes occur to the central auditory system (CAS) with aging as well. CHABA (1988) reviewed evidence that suggests that pathological changes occur along the entire auditory pathway, including the cochlear nucleus, superior olivary complex, inferior colliculus, lateral lemniscus, medial geniculate body and auditory cortex. These changes include cell loss, decreased cell size and decreased number of myelinated fibers (CHABA, 1988). Researchers hypothesize that CAS changes diminish encoding of the auditory signal and/or increase the level of neural background noise (Gordon-Salant & Fitzgibbons, 1995a). These changes are particularly evident when the CAS is taxed, reducing the “acoustic redundancy inherent in the speech stimulus” (Gordon-Salant & Fitzgibbons, 1995b, p.1151). To examine CAS function independent of any peripheral hearing loss, researchers measured performance of older adults with normal peripheral hearing on speech tests in background noise, reverberation, and with time compression. Gordon-Salant and Fitzgibbons (1995a) compared performance of elderly listeners and young listeners with normal peripheral hearing on the Revised Speech Perception in Noise Test (R-SPIN) (Bilger, Nuetzel, Rabinowitz & Rzeczkowski, 1984) under multiple degraded conditions, including noise, temporal distortion and reverberation. The authors found that even in mildly-distorted temporal conditions, older normal-hearing subjects performed worse than the younger normal-hearing subjects, suggesting older adults have a “reduced functional signal-to-noise ratio (SNR) for a range of signal degradation conditions” independent of peripheral hearing loss (p.1151). Similarly, Helfer and Wilber (1990) found older adults with minimal peripheral hearing loss performed significantly worse than normal-hearing younger adults on the perception of nonsense syllables in several reverberant and noisy conditions. Dubno, Dirks and Morgan (1984) also observed differences in speech recognition in background babble between normal-hearing young adult and older adult listeners. All three of these studies also compared performance between hearing-impaired younger and older adults on their respective tasks. While Helfer and Wilber (1990) concluded comparisons of these groups could not be made in their study due to differences in hearing thresholds, both Gordon-Salant and Fitzgibbons (1995a) and Dubno et al. (1984) found that, when pure tone thresholds were matched, the older hearing-impaired groups performed significantly worse than the younger hearing-impaired groups on tasks of temporally-distorted speech and speech in background babble, respectively, again suggesting that observed auditory performance deficits cannot be explained by peripheral hearing loss alone.

One explanation for the above findings is that standard measures of peripheral function, such as pure tone testing, are not sensitive to the full spectrum of deficits that arise with peripheral hearing loss, including impaired frequency selectivity and temporal resolution (Helfer & Wilber, 1990). However, a more likely explanation is that difficulties understanding speech in background noise arise at least in part from deficits in central auditory processing. The prevalence of central auditory processing disorders (CAPD) calculated from studies of the elderly population ranges anywhere from 10 to 20%, to 80 to 90%, depending on criteria for constituting "disorder," test battery, and several other factors (Humes, 1996). It should be noted that while the aforementioned studies indicate an age-related decline in central auditory processing as seen by degraded speech recognition, other studies have not found this age factor or otherwise have not found it consistently across measures of speech recognition. Jerger (1992), for instance, divided 137 participants aged 50-90 years into four threshold-matched age groups and studied their performance on four speech audiometric measures: Phonemically-Balanced (PB) words, Speech Perception In Noise (SPIN) test for both high- and low- predictability sentences, and the Synthetic Sentence Identification Test (SSI). A negative correlation between age and performance was found for all measures, however only the age trend for the SSI was statistically significant. In a similar study, Dubno, Lee, Matthews and Long (1997) performed two separate analyses to investigate age-related differences in speech recognition. First, they divided the 129 participants aged 55-84 years into three age groups, matched auditory thresholds to within 5 dB, and compared scores for a battery of speech recognition materials. No significant age-related differences in speech recognition were found with any measure using this analysis. In the second analysis the authors "used partial correlations to adjust both score and age for their association with average thresholds" (p.444). The only significant declines in speech recognition were for male subjects. While both of these studies showed age-related trends in certain instances, they highlight the difficulty that occurs when looking for such trends. Because peripheral hearing loss accounts for most of the decline of speech recognition in background noise with age, many other study parameters, such as test material, noise stimuli, gender, age group definitions, and degree to which thresholds are matched become important factors that can alter the outcome of the study.

In addition to the general effects of biological aging, a second hypothesis suggests that CAS changes with aging result from "the effects of removal or attenuation of neural input from ears that exhibit peripheral pathology" (Chisolm et al., 2003, p.4). Evidence exists that functional changes occur in the brain and central auditory pathways as a results of auditory deprivation (Neuman, 2005). For instance, Scheffler, Bilecen, Schmid, Tschopp and Seelig (1998) performed functional Magnetic Resonance Imaging (fMRI) on 10 subjects with normal bilateral hearing and 5 subjects with profound unilateral hearing loss, for both monaural and binaural signals (1000 Hz pulsed sine tones presented at 95 dB SPL). The authors found that the cortical response of the normal-hearing subjects was strongest in the contralateral hemisphere for monaural signals and nearly equal between the hemispheres for binaural signals. In contrast, they found the cortical response for subjects with profound unilateral hearing loss was nearly equal between the hemispheres for both monaural and binaural signals. The authors attributed cortical reorganization to plasticity of the CAS due to auditory deprivation, as the brain receives normal input from one ear and "attenuated and distorted" input from the hearing impaired ear. Over time, "the behavioral consequence is poorer than expected speech recognition performance in the impaired ear" (Neuman, 2005, p.178). This finding is illustrated in studies of monaurally-fitted patients with bilaterally symmetrical sensorineural hearing losses (BSSHL), which essentially creates a “relative” auditory deprivation. Silman, Gelfand and Silverman (1984) measured pure tone thresholds, speech recognition thresholds (SRTs), and speech recognition scores for the two ears of subjects with BSSHL who were monaurally fitted and subjects who were bilaterally fitted with hearing aids. Performance on these measures, compared before the hearing aid fittings and 4-5 years after the fittings, revealed that the speech recognition scores in the unaided ear of monaurally-fitted subjects declined significantly over time, though thresholds and SRTs remained stable. Performance on all three measures remained stable for the bilaterally-fitted subjects.

It should also be noted that people with unilateral or asymmetrical sensorineural hearing loss often have difficulties in background noise beyond those that arise from peripheral hearing loss, biological aging, or auditory deprivation. The brain is wired to receive and combine inputs from both ears, using subtle interaural time differences (ITDs) and interaural level differences (ILDs) to localize low frequency and high frequency information, respectively (Joris, Smith & Yin, 1998). In cases of unilateral hearing loss, the brain receives auditory information that is “off balance,” which leads to rearrangement of binaural connections in the auditory brainstem (Scheffler, et al. 1998), thus resulting in poorer localization abilities. This in turn impacts several psychoacoustic processes that utilize these spatial cues to segregate speech and background noise. One example is the loss of the masking level difference (MLD) phenomenon, also known as binaural squelch, in which a listener is best able to distinguish a signal in the presence of background noise when listening binaurally (Cox & Bisset, 1984). Without symmetrical binaural hearing, a person is unable to detect phase differences between the signal and masker, resulting in a decreased ability to separate speech from background noise. Additionally, a person with asymmetrical hearing loss has difficulty listening in background noise because the benefit of head diffraction effects is lost. Sounds, particularly high frequency sounds, create a “shadow” as they diffract around the head, resulting in different signal-to-noise (SNR) ratios at each ear. A person with normal hearing is able to selectively attend to the ear with the better SNR. A person with a unilateral or asymmetrical hearing loss loses this ability, and will have difficulty understanding speech or any signal presented on the side of the poorer ear. Head shadow effects are evidenced by cochlear implant studies, which reveal improved speech-in-background noise performance when hearing aids and cochlear implants are worn in opposite ears (binaural/bimodal hearing), (i.e.,Ching, Incerti, Hill & van Wanrooy, 2006; Litovsky, Parkinson, Arcaroli & Sammeth, 2006). Binaural hearing results in a 2-3 dB SNR improvement for suprathreshold stimuli, i.e., speech (Ching, 2005), thus the behavioral consequence of the loss of these processes is a decreased ability to understand speech in the presence of background noise. Persson et al. (2001) compared PB monosyllabic word speech recognition scores in background noise for 16 normal-hearing subjects in a free field condition, both binaurally and monaurally (using a hearing protector in one ear). The authors found 17% to 18% better speech recognition scores in binaural conditions as opposed to monaural conditions. Several other studies have revealed a binaural advantage for speech recognition in noise as well (i.e., Persson, P., Harder, H., Arlinger, S. & Magnuson, B., 2001; Freyaldenhoven, M., Plyler, P., Thelin, J. & Burchfield, S., 2006).

Neuman (2005) stated the most effective way to examine senescent changes in the CAS is to perform electrophysiological tests. Comparisons of automatic brainstem response (ABR) latencies between older adults and younger adults have revealed significantly longer absolute and interpeak latencies for the older adult subjects in some studies, when the ABR was elicited with fairly high stimuli and the amount of high-frequency hearing loss is controlled (Rawool, 2007a).

These findings suggest slower processing within the auditory brainstem. Similarly, some studies also suggest slower processing within the thalamus and primary auditory cortex as seen by prolongation of Pa latencies in auditory middle latency response (AMLR), and slower processing within the temporal and parietal lobes as seen by increased latencies on auditory late response (ALR) measures (Rawool, 2007b). However, it should be noted that for all three of the aforementioned measures, some studies (i.e. Chambers & Griffiths, 1991; Ottaviani, Maurizi, D'Alatri & Almadori, 1990; Anias, Lima & Kos, 2004) did not find any age effects and those that did noted significant variability among subjects. Interestingly, when comparing studies of ABR, AMLR, and ALR and speech recognition performance, Rawool (2007b) reported that increased latencies on any of the three electrophysiological tests may be at least partially related to declines in speech recognition.

Finally, researchers have also speculated that difficulties older adults have recognizing speech, including in background noise, may be due at least in part to declines in general cognitive functioning, including processes such as alertness, attention, memory, and overall intelligence (Rawool, 2007a). Studies have shown that slower processing occurs across these general cognitive processes with age (Chisolm et al., 2003). Researchers have attempted to find a relationship between speech recognition difficulties and cognitive decline in older adults (Jerger, 1992; Jerger, Jerger, Oliver & Pirozzolo, 1989; Humes, Watson, Christensen, Cokely, Halling & Lee, 1994; Frisina & Frisina, 1997). However, because speech recognition difficulties in older adults are attributed primarily to hearing thresholds, and to a lesser degree central auditory processing deficits, a strong link between degraded speech recognition and cognitive decline has not been found. Jerger et al. (1989), for instance, determined CAS and cognitive status in 130 elderly subjects with varied sensorineural hearing loss aged 51-91 years. The researchers administered the Synthetic Sentence Identification test (SSI), the SPIN, and the Dichotic Sentence Identification test (DSI), and categorized subjects as having CAPD if they scored below normal on any one of the three measures. Subjects also completed 9 measures of cognitive function, which a neuropsychologist interpreted and identified subjects with some degree of “cerebral dysfunction.” In examining congruence of disorders, the researchers determined that “central auditory status was abnormal in the presence of normal cognitive function in 23% of the subjects, and central auditory status was normal in the presence of cognitive deficit in 14% of the subjects” (p.79). Twenty-seven percent of subjects presented with both central auditory and cognitive abnormalities. Based on these results, the researchers concluded that speech recognition deficits, as seen on the three speech measures used in the study, could not be explained “as the consequence of concomitant cognitive decline” (p. 86).

Chapter 3

Evidence-based review: Speech recognition testing

Regardless of the cause, difficulty in background noise is the catalyst that drives many patients to seek a comprehensive audiological evaluation. Despite this fact, most diagnostic test batteries only include speech recognition tasks performed in quiet, with the speech recognition threshold (SRT) and supra-threshold word recognition score being the most commonly administered measures (Wiley, Stoppenbach, Feldhake, Moss & Thordardottir, 1995). Audiologists routinely use this information to identify and differentiate different auditory disorders. For instance, a word recognition score that is disproportionately poor for a given degree of hearing loss or that is significantly different over time or between the ears can characterize retrocochlear pathology; indicating the need for further investigation (Dubno, Lee, Klein & Matthews, 1995; Thornton & Raffin, 1978). Additionally, audiologists also frequently use word recognition scores as part of the hearing aid evaluation, fitting, and rehabilitation process, from which they make predictions of hearing aid success, establish realistic expectations, evaluate benefit, and recommend assistive technology. However, this "rehabilitative" function of the word recognition score has significant shortcomings, as it does not adequately assess a patient's communication abilities for the purposes of aural rehabilitation (Sweetow, 2007).

An obvious limitation of word recognition in quiet is that it is not representative of the "real world" and therefore does not reflect the range of listening conditions hearing-impaired listeners face on a daily basis. For instance, a study that examined noise levels of restaurants in the San Francisco Bay area found that nearly 78% of restaurants had signal-to-noise ratios (SNRs) considered detrimental to speech intelligibility for hearing-impaired patrons (Lebo et al., 1994). The same people who struggle in restaurants and other noisy environments often present with good or excellent word recognition scores in quiet. Keith and Talis (1970) measured word recognition scores in 170 hearing-impaired veterans and found that approximately 60% obtained word recognition scores of 90% or better. This study and others suggest a ceiling effect exists and word recognition scores measured in quiet are simply not sensitive enough to the communication difficulties in background noise that occur for patients with sensorineural hearing loss (Beattie, Barr & Roup, 1997). Thus, it is not uncommon for an audiologist to hear "I can hear you well in your office but I really struggle when I'm in the 'real world.'"

Additionally, research indicates that speech recognition testing in quiet cannot be used to predict patients' difficulties understanding speech in background noise. Beattie et al. (1997) measured word recognition scores in quiet and in background noise for 51 normal-hearing and 30 hearing-impaired subjects. The researchers computed linear regression equations to assess whether the word recognition in quiet scores could predict scores in background noise. They determined the 95% confidence interval for predicting speech-in-background noise scores from speech-in-quiet scores to be ±20%, indicating speech-in-background noise abilities cannot be predicted and should therefore be measured directly.

Furthermore, although audiologists frequently use the word recognition score to counsel patients on realistic expectations and to evaluate hearing aid benefit, research suggests the word recognition score does not accurately predict hearing aid success. Walden and Walden (2004) evaluated the predictive value of 10 different measures for hearing aid success in 50 hearing aid users, as determined by two questionnaires that evaluated use, benefit, satisfaction and quality of life. The word recognition in quiet score, using Northwestern University Auditory Test No. 6 (NU-6) word lists, was included in the predictive measures. The researchers found that the word recognition in quiet score did not correlate significantly with either outcome questionnaire. Interestingly, only the aided and unaided QuickSIN score was significantly correlated with both outcome questionnaires, though this was dependent on age. Greater benefit and satisfaction on the outcome questionnaires was associated with lower SNR loss on the QuickSIN (Walden & Walden, 2004). Taylor (2007) reviewed 11 different studies, including Walden and Walden (2004), which examined the use of speech audiometry as predictive value of hearing aid success. Taylor reported that “none of the 11 studies showed a strong predictive relationship between pre-fitting speech test scores measured in quiet and self-reports of hearing aid outcome” (p. 1).

In contrast to speech recognition in quiet, the addition of background noise to speech recognition tasks makes them more comparable to “real world” communication and more sensitive to the difficulties background noise creates for elderly hearing-impaired patients. Test difficulty increases and ceiling effects are eliminated or reduced, allowing more subtle differences in speech recognition with age and hearing loss to be examined, as is seen in several studies that compared speech recognition measures in quiet and in background noise. For instance, Wiley et al. (1998) compared word recognition scores in both quiet and background noise to study the effects of aging on speech understanding. The researchers evaluated word recognition performance on NU-6 word lists in quiet and competing message for 3189 adults grouped by age. They determined that word recognition in competing message was poorer than word recognition in quiet across all age groups; however the greatest performance deficits were seen in the competing message condition, even after adjusting for degree of sensorineural hearing loss. The researchers concluded that “speech recognition measures in a background of competing message would be more sensitive to aging effects relative to the same measures in quiet” (p.197). Beattie et al. (1997) also assessed word recognition performance in quiet and in background noise to compare speech recognition abilities of normal-hearing and hearing-impaired subjects. The researchers found that, while scores were lower for the hearing-impaired group across all conditions, the biggest difference was in the speech-in-noise conditions; stating that, “whereas the two groups differ by only 10% in the quiet condition, in the noise conditions they differ by about 30%” (p.159). They found the hearing-impaired group exhibited scores that were about 20% poorer for the 15 dB SNR condition than the quiet condition, concluding subjects with mild-to-moderate sensorineural hearing loss “require a more favorable SNR than normal listeners to achieve comparable word recognition scores” (p.159). Other studies have also compared performance on various measures in quiet and in background noise to examine age, gender, and degree of hearing loss effects on speech recognition (Gordon-Salant, 1985; Gordon-Salant & Fitzgibbons, 1995b; Helfer & Wilber, 1990). As with Beattie et al. (1997), the findings of these studies suggest the addition of background noise increases the sensitivity of speech recognition measures and highlights performance differences between subject groups.

It should be noted that while speech-in-noise testing clearly has advantages over testing in quiet, it too has limitations. While several studies suggest speech-in-background noise testing is more sensitive to differences between normal and impaired ears, other studies did not report similar findings. An example is the Jerger (1992) study (described above), in which significant age-related decline in speech recognition abilities was not found using the SPIN. Furthermore, little evidence exists to suggest speech-in-background noise testing is better than testing in quiet for predicting hearing aid benefit, which may have important implications for audiologist trying to incorporate evidence-based principles into their protocols. Taylor (2007) found that, like speech recognition in quiet, speech-in-background noise measures were also generally poor predictors of hearing aid success; only noting a weak positive predictive value for sentence-type speech-in-background noise measures. Although Walden and Walden (2004) found a significant correlation between QuickSIN score and benefit as measured by two outcome questionnaires, this correlation was attributed to the effects of age, as partial correlation to remove these effects resulted in a relationship between QuickSIN score and benefit that was no longer significant.

The practical considerations of implementing routine speech-in-noise testing must be examined as well. While most currently-available speech-in-noise tests take less than 10 minutes to administer, these tests and the time they take are not reimbursable according to current Medicare guidelines. However, Sweetow (2007) noted that in 2006, the Centers for Medicare and Medicaid Services created new CPT codes (92626 and 92627) “that implicitly recognized the need for an appraisal of residual auditory function beyond what the pure-tone audiogram provides” (p. 26).

While speech-in-background noise measures have been used extensively for research purposes, these measures are rarely included in standard diagnostic protocols. However, with an increasing focus on rehabilitation, many audiologists, including Sweetow (2007) and Wilson (2004), report that the benefits of performing testing in an environment more representative of real-life situations outweighs these limitations and necessitates the inclusion of speech-in-background noise tests in ones’ routine test battery. Once the decision to include speech-in-background noise testing has been made, several test parameters must be considered. One such parameter is the type of background noise stimulus used, such as speech-spectrum noise versus multitalker babble. Sperry, Wiley and Chial (1997) compared performance of 18 normal-hearing listeners on the NU-6 in the presence of three background competitors: meaningful multitalker babble, meaningless multitalker babble in which the babble was recorded in reverse, and amplitude-modulated speech spectrum noise. They found the meaningful multitalker babble competing message had the most deleterious effect on speech recognition, and suggested this competition may be best for highlighting performance differences in individuals with sensorineural hearing loss. Additionally, meaningful multitalker babble is clearly more reflective of real-life situations faced by patients.

Another consideration is the SNR at which the stimulus and background noise are presented. While some currently-available speech-in-background noise measures require either the background noise or stimulus level to be changed with each presentation, other measures use set levels. Beattie et al. (1997) suggested a SNR should be used that will avoid both ceiling and floor effects, in order to provide the best separation of normal and hearing-impaired ears. They determined SNRs of 10-15 dB were needed to achieve this goal. These levels also have the additional advantage of being reflective of SNRs encountered in many real-world listening situations.

A third testing parameter clinicians should consider when implementing a speech-in-background noise testing protocol is whether to use sentence-based or word-based tests. Sentence-based tests are more representative of real-world listening environments and give the most accurate picture of how an individual understands in background noise (Wilson, 2004). However, sentence tests scores may be influenced by declines in auditory processing speed, memory, and other cognitive processes seen in the elderly (Gordon-Salant & Fitzgibbons, 1997).

Once the speech materials and levels are determined, clinicians must also consider the listening condition used to administer the test. If the goal is to represent real-life listening, binaural sound field presentation clearly outweighs monaural presentation via headphones, with the additional advantage of allowing comparison between unaided and aided performance. However, sound field testing introduces variability into the testing, such as varying azimuths of speakers and headshadow (Wilson, 2004). Bilger et al.(1984) compared performance on the SPIN under headphones and via loudspeaker, and found no significant difference on test scores. Thus, listening condition does not significantly affect test scores, at least for one measure of speech-in-background noise.

A final parameter to consider is on whom to perform speech-in-background noise testing. Strom (2006) reported only 49% of dispensing audiologists perform some form of speech-in-noise testing, although the report did not specify how frequently audiologists use this testing. It is reasonable to assume that many audiologists do not perform speech-in-noise testing routinely, but instead perform it on a case-by-case basis depending on a patient's self-reported difficulties in background noise. However, Wilson (2007) found "little or no systematic relationship between the patient's perceived ability to understand speech in noise and the measured ability of the patient to understand speech in noise" (p.17). Thus, Sweetow (2007) proposes that speech-in-background noise testing be performed on every patient for the purposes of determining aural rehabilitation needs. Several well-studied speech-in-background noise test measures are currently-available for clinical use. These measures include but are not limited to the following: QuickSIN, Bamford-Kowal-Bench Sentence-In-Noise test (BKB-SIN) (Niquette et al., 2003), Hearing In Noise Test (HINT) (Nillson, Soli & Sullivan, 1994), R-SPIN, and Words In Noise test (WIN) (Wilson, 2003). See Appendix A for a review of these speech-in-background noise measures.

According to Strom (2006), 62% of audiologists who perform speech-in-background noise testing administer the QuickSIN. The QuickSIN, a shortened version of the original Speech In Noise (SIN) test, is comprised of sentences recorded in four-talker babble. Each of the twelve QuickSIN lists has six sentences, one sentence at each signal-to-noise ratio (SNR) of 25, 20, 15, 10, 5, and 0 dB. These SNRs encompass the range of normal to severely-impaired performance in noise. Sentences may be presented under headphones or through sound field speakers. Each sentence has five key words that are scored as correct/incorrect. The raw score is then calculated in terms of "SNR loss". SNR loss is defined as the "increased signal-to-noise ratio required by an individual to understand speech in noise, as compared to normal performance." Norms are provided to determine whether a patient's SNR loss is "normal/near-normal," "mild," "moderate" or "severe," along with rehabilitation recommendations for each categorization. (Killion et al., 2004).

The BKB-SIN is similar in design to the QuickSIN in that it also estimates SNR loss. It is designed to be used for children and adults for whom the QuickSIN is too difficult. The BKB-SIN consists of 18 list-pairs that are equated for difficulty. As with the QuickSIN, sentences are presented in a four-talker babble, and listeners are required to repeat key words in the sentences correctly. Also comparable to the QuickSIN, a formula is provided to convert a patient's raw score into a "SNR loss," and norms and recommendations are provided (Niquette et al., 2003).

The HINT is the second most commonly used speech recognition measure in background noise, reportedly used by 14% of dispensing audiologists who perform speech-in-background noise testing (Strom, 2006). The HINT is designed to measure speech recognition thresholds in both quiet and noise. The test consists of 25 lists of 10 sentences and noise that is matched to long-term average speech. Patients repeat sentences both in quiet, and in noise coming from different directions. Using an adaptive procedure, a reception threshold for sentences is obtained while noise is presented at a constant level. All words in the sentence must be repeated correctly in order for it to be marked as correct. Scores are then interpreted in terms of SNR, and compared with normative data to determine the patient's relative ability to hear in noise (Nillson et al., 1994).

Another sentences-in-background noise test, the R-SPIN, consists of 8 lists of 50 sentences. Unlike the previous two measures, however, only the last word of each sentence is considered the test item and must be repeated correctly. Half of listed sentences contain test items classified as having high predictability, indicating that the word is very predictable given the sentence context. The other half of listed sentences contain test items classified as having low predictability, indicating that the word is not predictable given sentence context. Recorded sentences come with a speech babble-type noise that can be presented at various S/N ratios, although a recommended 8-dB SNR is typically used (Bilger et al., 1984).

The WIN test, recently developed by Wilson (2003), evaluates speech understanding in a background of multitalker babble at several SNRs. Unlike the previous three measures, the WIN is a word-based test designed solely for measurement under headphones. The original test consisted of 70 monosyllabic words from the NU-6 word lists, with 10 words being said at each of seven SNRs from 24 to 0 dB SNR, in 4 dB increments. The cut-off point is determined by the SNR level at which all 10 words are heard incorrectly. To make the test more clinically-appropriate, Wilson and Burks (2005) developed two equivalent 35-word lists in which 5 words are presented at each SNR, cutting the test time in half. An advantage to this test is that it utilizes the same materials used to measure word recognition in quiet (recorded NU-6 word lists), allowing for direct comparison between speech recognition abilities in quiet and in background noise.

Wilson, McArdle and Smith (2007) examined performance differences between four of the above measures in 24 normal-hearing and 72 hearing-impaired subjects. Subjects completed the QuickSIN, BKB-SIN, HINT and WIN. The authors determined the 50% points for the listeners with normal hearing were in the 1- to 4-dB SNR range and for the listeners with hearing loss in the 5- to 14-dB SNR range. Furthermore, they found the WIN and Quick-SIN showed greater separation between the normal-hearing and hearing-impaired groups, suggesting these materials are more sensitive measures of performance in background noise than the BKB-SIN and HINT. The authors proposed that either the QuickSIN or WIN be incorporated into routine audiologic test batteries, depending on individual clinician preference for sentence or word testing, respectively.

Chapter 4

Evidence-based review: Rehabilitation strategies for improving speech understanding in background noise

The recent push from many audiologists to include speech-in-noise testing in standard clinical practice stems from a growing effort to manage a patient's global communication needs, beyond simply fitting a patient with hearing aids. As Sweetow (2007) states, "hearing aids may (or may not) be one component of an overall rehabilitation plan, but a rehabilitation plan is not a component of a hearing aid fitting….instead, hearing aids should supplement the global plan of communication treatment" (p.26).

This trend is precipitated by a body of evidence that indicates even the most sophisticated digital hearing aids have limitations in adverse listening environments. Kochkin (2005) reported that, while 71% of customers reported overall satisfaction with their hearing aids, nearly 49% reported being dissatisfied with their hearing aid(s)' performance in noisy situations. Hornsby, Ricketts and Johnson (2006) explained that these limitations result from the masking effects of the background competition. Two types of masking contribute to speech-recognition difficulties. Energetic masking occurs in the auditory periphery, when the neural excitation caused by the background competition is greater than the excitation caused by the speech stimulus. In contrast, informational masking has a more "central" origin, and commonly arises when the background competition is a speech stimulus. Hornsby et al. state, "In cases where informational masking occurs, both the target speech and competition are audible to the listener, yet the listener has difficulty separating the target and competition due to similarities in their temporal and/or semantic structure" (p. 433). The authors further suggest that, while omnidirectional hearing aids may improve speech recognition under energetic masking conditions, they offer limited benefit when informational masking occurs. They conducted a study in which they assessed speech recognition abilities of 15 normal-hearing subjects, and 15 hearing-impaired subjects in both aided and unaided conditions. The HINT was administered in six speech and masker conditions that were expected to produce varying amounts of informational masking. The authors determined that omnidirectional hearing aids were ineffective at improving speech recognition abilities when both energetic and informational masking sources were present. This is a significant finding, as everyday conversational speech environments often have varying degrees of informational masking present in the background noise.

On the other hand, Hornsby and Ricketts (2007) determined that directional microphones do improve speech recognition abilities in the presence of energetic and informational masking. They administered the HINT to 14 hearing-impaired subjects in both omnidirectional and directional aided conditions. In a similar set up to Hornsby et al. (2006), six different speech and noise configurations were utilized to vary the amount of expected informational masking. The authors found a significant directional benefit for speech recognition in all conditions, suggesting directional microphones can aid speech understanding in many types of background noise encountered during everyday situations. Significant directional benefit for speech recognition in background noise has been noted in several other studies as well (Wouters, Litière & van Wieringen, 1999; Ricketts & Henry, 2002, Palmer, Bentler & Mueller, 2006a.; Valente, Mispagel, Tchorz & Fabry, 2006; Blamey, Fiket & Steele, 2006.) Wouters et al. (1999)

evaluated directional benefit by comparing speech recognition in background noise in 10 binaural hearing aid users, using omnidirectional and directional hearing aid configurations. Bisyllabic words and sentences were presented in three types of background noise: speech-weighted noise, traffic noise, and restaurant noise. The researchers calculated SNRs for each condition, and found an average 3.4 dB SNR improvement with the directional microphone configuration for noise presented in the 90 degree azimuth. Ricketts and Henry (2002) compared adaptive directional, fixed directional, and omnidirectional hearing aid performance on the HINT and Connected Speech Test (CST) in 3 fixed noise conditions and one panning noise condition. They concluded both the fixed and adaptive directional hearing aids improved speech recognition performance over omnidirectional hearing aids in all conditions. Furthermore, they reported a significant advantage of adaptive directionality over fixed directionality in some conditions. As hearing impaired adults need as much as a 4 to 18 dB higher SNR in order to obtain speech recognition scores similar to individuals with normal hearing, it is logical the directional microphone systems, proven to increase SNR, effectively improve speech recognition in background noise (Valente, Crandell, Lewis, & Enrietto, 2003).

While the above studies reveal a clear advantage to using directional microphones in background noise, speech recognition improvement can be limited. Mills (2007) stated a goal of directional microphone systems is “focusing the directionality of audition toward the signal and away from the noise” (p.60). However, certain environmental factors, such as reverberation and distance from the speaker, hamper a directional microphone system’s ability to obtain this goal. Ricketts and Hornsby (2003) examined the impact of speaker-to-listener distance and reverberation on directional benefit. They measured aided sentence recognition performance in background noise for 14 hearing-impaired subjects in both omnidirectional and directional modes. Speech recognition was measured in both a low- and moderately-reverberant environment at three different loudspeaker-to-listener distances. Directional benefit was still noted in all conditions, however, a significant decrease in benefit was measured with increasing distance in moderate reverberation. Furthermore, subjective reports of directional benefit suggest that the advantages noted in controlled test environments may not transfer to real-world improvements (Palmer, Benter & Mueller, 2006b.). Mills and Martin (2007) explained that limitations of directionality arise from the complexity of how normal-hearing individuals decipher various incoming sounds. In a process referred to as auditory scene analysis, normal-functioning auditory systems are able to detect characteristics of auditory signals such as pitch, timbre, and spatial location, and use these characteristics to "perceptually segment many simultaneously occurring sounds into perceptually distinct auditory streams" (p.66). Furthermore, Mills and Martin (2007) states "to date, digital signal processing (DSP) and directional microphones have failed to duplicate this ability artificially" (p. 66).

As this remark indicates, current DSP strategies such as digital noise reduction and spectral enhancement have limitations improving speech in background noise. Digital noise reduction systems are designed to identify noise in the environment and digitally reduce it, thereby increasing the SNR of the signal. The most common noise reduction system divides the incoming signal into bands and reduces the gain in the bands when the speech-to-noise ratio (SNR) gets too low. While this reduces the noise, a major drawback is that it also reduces the speech signal in these bands (Venema, 1999). Yuen, Kam and Lau (2006) compared the ability of hearing aids to reduce the effect of background noise on speech recognition using a directional microphone system and a multichannel noise reduction system. The best speech recognition improvements were noted in conditions in which directional microphones were used, suggesting the noise reduction did not provide any added benefit for speech recognition. In contrast, spectral enhancement systems are designed to account for the loss of frequency selectivity that occurs in hearing-impaired ears, by artificially sharpening peaks in the speech spectrum. A prominent limitation of this technology is that, even with sharpened spectral input, the hearing aids are still adding gain to the signal, "stimulating the cochlea at moderate to high levels where tuning is no longer narrow even in a normal ear" (Trine & Van Tasell, 2002, p.37). Thus, despite advancements in digital signal processing and the abundance of heavily-promoted noise reduction and speech-enhancement algorithms in the hearing aid industry, neither of these methods has been proven to improve speech recognition in background noise (Trine & Van Tasell, 2002; Moore, 1996). In terms of hearing aid technology, then, directional microphones are the only feature that clearly improves SNR, thereby improving speech recognition in background noise.

The most successful way to enhance communication in adverse listening environments, however, is to use technology beyond hearing aids, namely frequency modulation (FM) systems or similar personal listening devices (Valente et al., 2003). The FM transmitter picks up the speaker's words within inches of his or her mouth, and sends the signal directly to the FM receiver at or near the listener's ears. Thus, the signal is virtually unaffected by distance, reverberation, and background noise (Crandell et al., 2003). Valente et al. (2003) reported that, while directional microphones provide a SNR improvement of 3-8 dB over omnidirectional microphones, FM systems can improve the SNR by up to 20 dB. The authors compared performance on the HINT using directional microphones and FM technology. As expected, performance in directional mode exceeded that in omnidirectional mode. However, FM provided significantly greater speech recognition improvement than the directional microphone condition. Overall, the best speech recognition scores were obtained when the subjects used binaural hearing aids set to the FM-only mode. Thus, the greater increase in SNR of FM technology over directional microphones results in significantly better speech understanding for hearing-impaired adults in difficult listening situations. This advantage is particularly evident in the subset of hearing-impaired adults who have auditory processing deficits, for whom even the most sophisticated directional microphone systems and digital signal processing may not provide adequate benefit (Jerger, Chmiel, Florin, Pirozzolo, &Wilson, 1996; Carter, Noe, & Wilson, 2001; Stach, Loiselle, & Jerger, 1991).

The benefits of FM technology that are visible in the laboratory setting have also been shown to transfer to subjective patient benefit. Chisolm et al. (2003) examined FM performance in 31 VA patients who had all worn hearing aids and said they lacked satisfaction in at least one communication situation. After a seven-week trial period with an FM system, performance on the Communication Profile for the Hearing Impaired (CPHI) revealed a significant improvement in all five listening situation subcategories: social, work, home, average, and adverse. In particular, the average rating of effective communication increased from “occasionally” for the hearing aid only condition, to “frequently” for the FM condition. In the same study, the authors also compared the satisfaction of the VA patients with FM technology in different listening situations to the results reported in the MarkeTrak VI survey for people with hearing instruments alone. For the small group, worship, television, restaurant, car, and telephone situations, the proportion of satisfied patients increased, and dissatisfied patients decreased significantly from the hearing aid only condition. Finally, Chisolm et al. (2003) also administered the COSI to the same VA subjects. After using the FM system, 94% of subjects reported improvement for conversations with one or two people in noise, 71% reported improvement for group communication in noise, and 88% reported improvement for church or meetings. Improvement was also shown for easier listening environments, such as conversations in quiet. The only drawback to FM technology appears to be hearing-impaired users' unwillingness to utilize this technology (Jerger et al. 1996; Boothroyd, 2004). Kochkin (2005) reported that less than 1% of consumers own an FM assistive listening device. Several reasons have been proposed to explain the low penetration of FM technology in the hearing-impaired adult population. These include cost, complexity of device, increased attention to the hearing loss due to device visibility, and difficulty using the device in noise (Noe et al., 2003).

Another method that has been gaining recent attention for improving speech recognition in background noise is auditory training. Although the audibility of a speech signal can typically be immediately restored to a sufficient degree with hearing aids, the listener may need time to learn to interpret the newly restored information, as peripheral hearing loss can lead to central auditory changes (Burk, Humes, Amos & Strauser, 2006). Auditory training uses the principles of auditory plasticity and learning to "rewire" the brain for processing and interpreting sound (Neuman, 2005). This "rewiring", or cortical reorganization, is evidenced by physiological measures which reveal changes in brainstem and cortical activity post-auditory training (Neuman, 2005). The concept of auditory training has been utilized since audiology's infanthood in the post- World War II era; Jerger (1996) reported Carthart provided auditory training for hearing-impaired veterans. Since then, the use of auditory training strategies has substantially declined, likely due to the time and money associated with such training (Ross, 2005). However, with renewed desire to provide patients with a comprehensive aural rehabilitation plan, there has been a surge of interest in modern time- and cost-effective auditory training techniques, particularly with the advent of the Listening And Communication Enhancement (LACE™)

program, designed by Sweetow and Sabes (2006). LACE™ is a "home-based, interactive adaptive computer program designed to engage the adult hearing-impaired listener in the hearing-aid-fitting process, provide listening strategies, build confidence, and address cognitive changes characteristic of the aging process" (p.538). Training is conducted for 30 minutes, five days per week, for a period of four weeks. Exercises address several peripheral, central, and cognitive-based auditory skills shown to decline with aging, including degraded speech recognition, speech recognition in competing message, working auditory memory, and speed of processing. In addition, the software provides exercises to enhance use of contextual/linguistic cues and communication strategies (Sweetow & Sabes, 2006). Much attention is focused on LACE™ due to a growing body of research that show LACE™ results in communication improvement. Sweetow and Sabes (2006) obtained several outcome measures on 65 subjects randomly placed into a group receiving LACE™ or a control group. Outcome measures included two speech-in-background noise measures (QuickSIN and HINT), and two outcome questionnaires. A subset of subjects also completed two objective tests measuring processing speed and working auditory memory. All measures, with the exception of the HINT, revealed significant improvements for the group receiving LACE™. The authors suggested that benefit was not noted on the HINT because it is a less sensitive measure of difficulties in background noise (Wilson et al., 1997). In particular, 45% of trained subjects demonstrated improved QuickSIN scores, compared to 0% of the untrained group, suggesting the strengthened listening skills associated with LACE™ training result in improved speech understanding in background noise beyond the tasks required of the program. Although LACE™ is currently the most popular individual auditory training program, several other home-based computer auditory training programs are available for patient use as well, such as Sound and Beyond, Seeing and Hearing

Speech, and Conversation Made Easy. Many auditory training programs arose from cochlear implant and pediatric research and rehabilitation, as auditory training is often routinely administered in these populations (Ross, 2005).

Finally, there is also evidence to suggest that limited improvement of speech recognition abilities in background noise can be obtained for some individuals by using appropriate communication strategies, such as clear speech and visual cues (Ross, Saint-Amour, Leavitt, Javitt & Foxe, 2007; Grant, Walden & Sietz, 1998; Schum, 1996). Helfer (1998) examined older adults' ability to understand clear and conversationally spoken nonsense sentences presented in both auditory-only (A-only) and auditory-visual (AV) modes. She determined older adults benefited from both clear speech and visual information, reporting, "the difference between A-only perception of conversational speech and AV perception of clear speech was approximately 30 percent" (p.240). However, age correlated negatively with AV performance, indicating that age-related changes to the visual system may actually reduce older adults' ability to integrate visual cues with auditory information. This finding was not observed in Cienkowski and Carney (2002), who determined that, at the syllable level, older adults are as successful as young adults at integrating auditory and visual information.

Table 1

Summary of Speech-In-Background Noise Tests

TEST	NOISE STIMULUS	SPEECH STIMULUS	SNR	LISTENING CONDITION
QuickSIN	Multi-talker babble	Sentences	Multiple	Headphones or sound field
BKB-SIN	Multi-talker babble	Sentences	Multiple	Headphones or sound field
HINT	Steady state speech-spectrum noise	Sentences	Multiple	Headphones or sound field
R-SPIN	Multi-talker babble	Sentences	8 dB (common)	Headphones or sound field
WIN	Multi-talker babble	Words	Multiple	Headphones

Chapter 5

Summary/Conclusions

Both anecdotal report and laboratory research clearly indicate that older adults experience difficulties hearing in noise that are disproportionate to difficulties hearing in quiet. This paper reviews an abundance of evidence that reiterates the need for assessing and managing these difficulties. Audiologists have traditionally omitted or limited these services due to practical concerns, unfamiliarity with tests or products, and tradition. While a plethora of literature explains why these services are advantageous, further examination is needed into how to reasonably incorporate these services in standard practice, so that these concerns are no longer valid. As audiologists, it is time to re-define our field as a rehabilitative profession and live up to our ethical obligation to address all of our patients' communication needs.

LIST OF REFERENCES

Anias, C., Lima, M. & Kos, A. (2004). Evaluation of the influence of age in auditory brainstem response. *Brazilian Journal of Otorhinolaryngology, 70,* 84-89.

Beattie, R., Barr, T. & Roup, C. (1997). Normal and hearing-impaired word recognition scores for monsyllabic words in quiet and noise. *British Journal of Audiology, 31,* 153-164.

Bilger, R.C., Nuetzel, J.M., Rabinowitz, W.M., & Rzeczkowski, C. (1984). Standardization of a test of speech perception in noise. *Journal of Speech and Hearing Research, 27,* 32-48.

Blamey, P., Fiket, H. & Steele, B. (2006). Improving speech intelligibility in background noise with an adaptive directional microphone. *Journal of the American Academy of Audiology, 17(7),* 519-530.

Boothroyd, A. (2004). Hearing aid accessories for adults: The remote FM microphone. *Ear &Hearing, 25(1),* 22-33.

Burk, M., Humes, L., Amos, N. & Strauser, L. (2006). Effect of training on word recognition performance in noise for young normal-hearing and old hearing-impaired listeners. *Ear & Hearing, 27(3),* 263-278.

Carter, A., Noe,C., & Wilson, R. (2001). Listeners who prefer monaural to binaural hearing aids. *Journal of the American Academy of Audiology, 12,* 261-272.

Chambers, R. & Griffiths, S. (1991). Effects of age on the adult auditory middle latency response. *Hearing Research, 51(1),* 1-10.

Ching, T. (2005). The evidence calls for making binaural-bimodal fittings routine. *The Hearing Journal, 58(11),* 32-41.

Ching, T., Incerti, P., Hill, M. & van Wanrooy, E. (2006). An overview of binaural advantages for children and adults who use binaural/bimodal hearing devices, *Audiology & Neuro-otology, 11 suppl. 1*, 6-11.

Chisolm, T., Noe, C., McArdle, R., Hemard, A., Abrams, H., Wilson, R., Reese, J., Koder, K., & Rost, L. (2003). FM technology use in adults with significant hearing loss part II: Outcomes. *ACCESS: Achieving Clear Communication Employing Sound Solutions, Proceedings of the First International FM Conference* (141-146), Chicago.

Chisolm, T., Williot, J. & Lister, J. (2003). The aging auditory system: Anatomic and physiologic changes and implications for rehabilitation. *International Journal of Audiology, 42*(Suppl. 2), 3-10.

Cienkowski, K. & Carney, A. (2002). Auditory-visual speech perception and aging. *Ear & Hearing, 23(5),* 439-449.

Committee on Hearing and Bioacoustics and Biomechanics. (1988). Speech understanding and aging. *Journal of the Acoustical Society of America, 83(3),* 859-895.

Cox, R. & Alexander, G. (1995). The Abbreviated Profile of Hearing Aid Benefit. *Ear & Hearing, 16,* 176-186.

Cox, R. & Bisset, J. (1984). Relationship between two measures of aided binaural advantage. *Journal of Speech & Hearing Disorders, 49(4),* 399-408.

Crandell, C., Lewis, M., Valente, L., Enrietto, J., Kreisman, B., & Kreisman, N. (2003). Functional health benefits of hearing aid and FM systems. *ACCESS: Achieving Clear Communication Employing Sound Solutions, Proceedings of the First International FM Conference (*53-59), Chicago.

Dubno, J., Dirks, D. & Morgan, D. (1984). Effects of aging and mild hearing loss on speech recognition in noise. *Journal of the Acoustical Society of America, 76(1),* 87-96.

Dubno, J., Lee, F., Klein, A. & Matthews L. (1995). Confidence limits for maximum word recognition scores. *Journal of Speech and Hearing Research, 38,* 490-502.

Dubno, J., Lee, F., Matthews, L. & Mills, J. (1997). Age-related and gender-related changes in monaural speech recognition. *Journal of Speech, Lanugage, and Hearing Research, 40,* 444-452.

Florentine, M., Buus, S., Scharf, B. & Zwicker, E. (1980). Frequency selectivity in normally-hearing and hearing-impaired observers. *Journal of Speech and Hearing Research, 23,* 646-669.

Freyaldenhoven, M., Plylor, P., Thelin, J. & Burchfield, S. (2006). Acceptance of noise with monaural and binaural amplification. *Journal of the American Academy of Audiology, 17,* 659-666.

Frisina, D. & Frisina, R. (1997). Specch recognition in noise and presbycusis: Relations to possible neural mechanisms. *Hearing Research, 106,* 95-104.

Gordon-Salant, S. (1989). Phoneme feature perception in noise by normal- and hearing-impaired subjects. *Journal of Speech & Hearing Research, 28, 87-95.*

Gordon-Salant, S. & Fitzgibbons, P. (1995a) Comparing recognition of distorted speech using an equivalent signal-to-noise ratio index. *Journal of Speech and Hearing Research,38(3),* 706-713.

Gordon-Salant, S. & Fitzgibbons, P. (1995b). Recognition of multiply degraded speech by young and elderly listeners. *Journal of Speech and Hearing Research, 38(5),* 1150-1156.

Gordon-Salant, S. & Fitzgibbons, P. (1997). Selected cognitive factors and speech recognition performance among young and elderly listeners. *Journal of Speech, Language, and Hearing Research, 40(2),* 423-431.

Grant, K., Walden, B. & Seitz, P. (1998). Auditory-visual speech recognition by hearing-impaired subjects: consonant recognition, sentence recognition, and auditory-visual integration. *Journal of the Acoustical Society of America, 103 (5 pt. 1),* 2677-2690.

Healy, E. & Bacon, S. (2006). Measuring the critical band for speech. *Journal of the Acoustical Society of America, 119(2),* 1083-1091.

Helfer, K. & Wilber, S. (1990). Hearing loss, aging, and speech perception in reverberation and noise. *Journal of Speech and Hearing Research, 33,* 149-155.

Hornsby, B. & Ricketts, T. (2007). Directional benefit in the presences of speech and speechlike maskers. *Journal of the American Academy of Audiology, 18 (1),* 5-16.

Hornsby, B., Ricketts, T. & Johnson, E. (2006). The effects of speech and speechlike maskers on unaided and aided speech recognition in persons with hearing loss. *Journal of the American Academy of Audiology, 17(6),* 432-437.

Humes, L. (1996). Speech Understanding in the elderly. *Journal of the American Academy of Audiology, 7,* 161-167.

Humes, L., Watson, B., Christensen, L., Cokely, C., Halling, D. & Lee, L. (1994). Factors associated with individual differences in clinical measures of speech recognition among the elderly. *Journal of Speech and Hearing Research, 37,* 465-474.

Jerger, J. (1992). Can age-related decline in speech understanding be explained by peripheral hearing loss? *Journal of the American Academy of Audiology, 3,* 33-38.

Jerger, J. (2006). Editorial: Auditory training. *Journal of the American Academy of Audiology, 17(8).*

Jerger, J., Chmiel, R., Florin, E., Pirozzolo, F., & Wilson, N. (1996). Comparison of conventional amplification and an assistive listening device in elderly persons. *Ear & Hearing, 17(6),* 490-504.

Jerger, J., Jerger, S., Oliver,T. & Pirozzolo, F. (1989). Speech understanding in the elderly. *Ear & Hearing, 10(2),* 79-89.

Joris, P., Smith, P. & Yin, T. (1998). Coincidence detection in the auditory system: 50 years after Jeffress. *Neuron, 21,* 1235-1238.

Killion, M., Niquette, P., Gudmundsen, G., Revit, L. & Banerjee, S. (2004). Development of a quick speech-in-noise test for measuring signal-to-noise ratio loss in normal-hearing and hearing-impaired listeners. *Journal of the Acoustical Society of American, 116(4),* 2395-2405.

Keith, R. & Talis, H. (1970). The use of speech in noise in diagnostic audiometry. *Journal of Auditory Research, 10,* 201-204.

Kochkin, S. (2005). MarkeTrak VII: Customer satisfaction with hearing instruments in the digital age. *The Hearing Journal, 58(9),* 30-37.

Lebo, C., Smith, M., Mosher, E., Jelonek, S., Schwind, D., Decker, K. et al. (1994). Restaurant noise, hearing loss, and hearing aids. *The Western Journal of Medicine, 161(1),* 45-49.

Litovsky, R., Parkinson, A., Arcaroli, J. & Sammeth, C. (2006). Simultaneous bilateral cochlear implantation in adults: a multicenter clinical study. *Ear & Hearing, 27(6),* 714-731.

Mills, R. & Martin, D. (2007). Why directional microphones don't work better? *Hearing Review, 14(10),* 60-66.

Moore, B. (1996). Perceptual consequences of cochlear hearing loss and their implications for the design of hearing aids. *Ear & Hearing, 17(2),* 133-161.

Moore, B. (2004). Dead regions in the cochlea: Conceptual foundations, diagnosis, and clinical applications. *Ear & Hearing, 25(2),* 98-116.

Moore, B., Huss, M., Vickers, D., Glasberg, B. & Alcantara, J. (2000). A test for the diagnosis of dead regions in the cochlea. *British Journal of Audiology, 34,* 205-224.

Neuman, A. (2005). Central auditory plasticity and aural rehabilitation of adults. *Journal of Rehabilitation Research & Development, 42(4),* p.169-186.

Nilsson, M., Soli, S., & Sullivan, J. (1994). Development of the Hearing in Noise Test for the measurement of speech reception thresholds in quiet and in noise. *The Journal of the Acoustical Society of America, 95,* 1085–1099.

Niquette, P., Arcaroli, J., Revit, L., Parkinson, A., Staller, S., Skinner, M., & Killion, M. (2003, March). Development of the BKB-SIN Test. Paper presented at the annual meeting of the American Auditory Society, Scottsdale, AZ.

Noe, C., McArdle, R., Chisolm, T., Koder, K., Rost, L., Hemard, A., Wilson, R., Abrams, H., & Reese, J. (2003). FM technology use in adults with significant hearing loss part II: Candidacy. *ACCESS: Achieving Clear Communication Employing Sound Solutions. Proceedings of the First International FM Conference* (113-120), Chicago.

Ottaviani, F., Maurizi, M., D'Alatri, L. & Almadori, G. (1990). Auditory brainstem responses in the aged. *Acta Otolaryngology Suppl., 476,* 110-112.

Oxenham, A. & Bacon, S. (2003). Cochlear compression: Perceptual measures and implications for normal and impaired hearing. *Ear & Hearing, 24(5)*, 352-366.

Palmer, C., Bentler, R. & Mueller, G. (2006a.) Evaluation of a second-order directional microphone hearing aid: I. Speech perception outcomes. *Journal of the American Academy of Audiology, 17(3),* 179-189.

Palmer, C., Bentler, R. & Mueller, G. (2006b.). Evaluation of a second-order directional microphone hearing aid: II. Self-report outcomes. *Journal of the American Academy of Audiology, 17(3),* 190-201.

Persson, P., Harder, H., Arlinger, S. & Magnuson, B. (2001). Speech recognition in background noise: monaural versus binaural listening conditions in normal-hearing patients. *Otology & Neurotology, 22(5),* 625-630.

Preminger, J., Carpenter, R. & Ziegler, C. (2005). A clinical perspective on cochlear dead regions: Intelligibility of speech and subjective hearing aid benefit. *Journal of the American Academy of Audiology, 16(8),* 600-613.

Rawool, V. (2007a). The aging auditory system part 1: Controversy and confusion on slower processing: Evidence for slower processing at and below the brainstem level using objective measures. *The Hearing Review, 14(7),* p.14-18.

Rawool, V. (2007b). The aging auditory system part 2: Slower processing and speech recognition: How slower processing in the aging auditory system is related to speech recognition. *The Hearing Review, 14(9),* p.36-41.

Ricketts, T. & Henry, P. (2002). Evaluation of an adaptive, directional-microphone hearing aid. *International Journal Of Audiology, 41(2),* 100-112.

Ricketts, T. & Hornsby, B. (2003). Distance and reverberation effects on directional benefit. *Ear & Hearing, 24(6),* 472-484.

Ross, L., Saimt-Amour, D., Leavitt, V., Javitt, D. & Foxe, J. (2007). Do you see what I am saying? Exploring visual enhancement of speech comprehension in noisy environments. *Cerebral Cortex, 17(5),* 1147-1153.

Ross, M. (2005). Home-based auditory and speechreading training. *Hearing Loss Magazine, 26(6),* 30-37.

Scheffler, K., Bilecen, D., Schmid, N., Tschopp, K. & Seelig, J. (1998). Auditory cortical response in hearing subjects and unilateral deaf patients as detected by functional Magnetic Resonance Imaging. *Cerebral Cortex, 8(2),* 156-163.

Schum, D. (1996). Intelligibility of clear and conversational speech of young and elderly talkers. *Journal of the American Academy of Audiology, 7,* 212-218.

Schucknecht, H. & Gacek, M. (1993). Cochlear pathology in presbycusis. *The Annals of Otology, Rhinology, & Laryngology, 102(1 pt 2),* 1-16.

Silman, S., Gelfand, S. & Silverman, C. (1984). Late-onset auditory deprivation:Effects of monaural versus binaural hearing aids. *Journal of the Acoustical Society of America, 76(5),* 1357-1362.

Sperry, J., Wiley, T. & Chial, M. (1997). Word recognition performance in various background competitors. *Journal of the American Academy of Audiology, 8(2),* 71-80.

Stach, B., Loiselle, L., & Jerger, J. (1991). Special hearing aid considerations in elderly patients with auditory processing disorders. *Ear & Hearing, 12(6), Supplement,* 131s-138s.

Strom, K. (2006). The HR 2006 dispenser survey. *The Hearing Review, 1(6),*16-31.

Sweetow, R. (2007). Instead of a hearing aid evaluation, let's assess functional communication ability. *The Hearing Journal, 60(9),* 26-31.

Sweetow, R. & Sabes, J. (2006). The need for and development of an adaptive listening and communication enhancement (LACE™) program. *Journal of the American Academy of Audiology, 17(8),* 538-558.

Taylor, B. (2007). Predicting Real World Hearing Aid Benefit with Speech Audiometry: An Evidence-Based Review. *Audiology Online*. Retrieved Dec. 3, 2007 at www.audiologyonline.com.

Thornton, A. & Raffin, M. (1978). Speech discrimination scores modeled as a binomial variable. *Journal of Speech and Hearing Research*, *21*, 507-518.

Trine, T. & Van Tasell, D. (2002). Digital hearing aid design: Fact versus fantasy. *The Hearing Journal, 55(2)*, 36-42.

Valente, M., Crandell, C., Lewis, M., & Enrietto, J. Improving speech recognition in noise: Directional microphone and FM systems. *ACCESS: Achieving Clear Communication Employing Sound Solutions*. *Proceedings of the First International FM Conference* (39-52), Chicago.

Valente, M., Mispagel, K., Tchorz, J. & Fabry, D. (2006). Effect of type of noise and loudspeaker array on the performance of omnidirectional and directional microphones. *Journal of the American Academy of Audiology, 17(6),* 398-412.

Venema, T. (1999). Three ways to fight noise: Directional mics, DSP algorithms, and expansion. *The Hearing Journal*, *52(10)*, 58-62.

Walden, T. & Walden, B. (2004). Predicting success with hearing aids in everyday living. *Journal of the American Academy of Audiology, 15*, 342-352.

Wiley, T., Cruickshanks, K., Nondahl, D., Tweed, T., Klein, R. & Klein, B. (1998). Aging and word recognition in competing message. *Journal of the American Academy of Audiology, 9,* 191-198.

Wiley, T., Stoppenbach, D., Feldhake, L., Moss, K. & Thordardottir, E. (1995). Audiological practices: What is popular versus what is supported by evidence. *American Journal of Audiology, 4,* 26-24.

Wilson, R. (2003). Development of a speech in multitalker babble paradigm to assess word-recognition performance. *Journal of the American Academy of Audiology, 14,* 453-470.

Wilson, R. (2004). Adding speech-in-noise testing to your clinical protocol: Why and how. *The Hearing Journal, 57(2),* 10-18.

Wilson, R. & Burks, C. (2005). Use of 35 words for evaluation of hearing loss in signal-to-babble ratio: A clinic protocol. *Journal of Rehabilitation Research & Developmen, 42(6),* 839-852.

Wilson, R., McArdle, R. & Smith, S. (2007). An evaluation of the BKB-SIN, HINT, QuickSIN, and WIN materials on listeners with normal hearing and listeners with hearing loss. Journal of Speech, Language, and Hearing Research, 50(4), 844-856.

Wouters, J., Litière, L. & van Wieringen, A. (1999). Speech intelligibility in noisy environments with one- and two- microphone hearing aids. *Audiology, 38(2),* 91-98.

Yeun, K., Kam, A. & Lau, P. (2006). Comparative performance of an adaptive directional microphone system and a multichannel noise reduction system. *Journal of the American Academy of Audiology, 17(4),* 241-252.